Planning of Cellular Networks Enhanced by Energy Harvesting

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Abstract

We pose a novel cellular network planning problem, considering the use of renewable energy sources and a fundamentally new concept of energy balancing, and propose a novel algorithm to solve it. In terms of the network capital and operational expenditure, we conclude that savings can be made by enriching cellular infrastructure with energy harvesting sources, in comparison to traditional deployment methods.

Index Terms

Cellular networks, energy harvesting, renewable energy, energy balancing, network planing.

I. INTRODUCTION

Although equipping base stations (BSs) with Renewable Energy Sources (RESs), such as solar panels and wind turbines (either to support or replace traditional electric grid connection with energy harvest-

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ing [2]), has been proved technically feasible, the research on RES-powered cellular networks is still in its infancy. One of the fundamental questions to be answered is how to plan the topology of RES-enabled cellular networks (i.e. physical location of BS and the location of RES) to satisfy coverage in accordance with quality of service (QoS) needs (defined in some specific sense), while significantly reducing capital and operational expenditure (CAPEX and OPEX, respectively). Therefore, inspired by the studies of BSs deployment in traditional cellular networks [3], [4], this letter attempts to answer this question by formulating a novel optimization framework for planning the RES-enabled cellular network. As the problem is shown to be NP-hard, we build a heuristic for cellular topology planning consisting of two phases: (i) QoS-aware BS deployment and (ii) energy balancing connection. Numerical results show that the proposed heuristic brings CAPEX and OPEX savings in comparison to traditional network deployment methods.

II. System Model

Network Characterization: We consider an area where a cellular network must be deployed or enhanced/upgraded with new features. As downlink is the bottleneck of a cellular network (since far more traffic is sent over downlink than uplink) it needs to be handled first in network planning. We thus focus on downlink transmission. Then we assume a set of candidate sites for BS installment labeled $\mathcal{N} = \{1, \ldots, N\}$, with a respective installation cost c_n, $n \in \mathcal{N}$. Further, we assume a set of test points (TPs), i.e., centroids, where a given amount of traffic or a certain level of QoS service must be guaranteed [3, Sec. III-A], located at sites $\mathcal{M} = \{1, \ldots, M\}$. Expressly, TP can be interpreted as a (set of) user equipment in the cellular networks (with certain properties, e.g. minimum required signal to noise ratio, defined individually per each TP).

Energy Consideration: As BS n is connected to an electric grid consuming power $P_n^{(g)}$, $\forall n \in \mathcal{N}$, we aim to minimize the energy consumption at the network planning stage. We thus assume that each BS is equipped with RES, e.g., solar panel, wind turbine. The instantaneous (and aggregated from all energy sources) power delivery capacity of RES for BS n, Z_n, is a stationary stochastic process described by PDF $f_n^{(r)}(z_n)$. As a fundamental novelty, for potential energy delivery improvements, we assume that BSs can have *dedicated power line connections for energy balancing*[1] from other RESs. On the other hand RESs are not equipped with any battery to store energy (as fixed electric grid connection guarantees a constant energy supply in case of insufficient energy from RES). This assumption results in a lower bound for the system planning, noting however that our model can be extended to consider energy storage.

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[1]Note: this concept has been independently presented in [5] once our paper was already under review.

The power transferred from BS t to BS n (through its co-located RES) is denoted as $P_{t,n}$, while the associated (distance-dependent) cost, e.g. installation, maintenance, operation, of connecting BS t and n is denoted as $c_{t,n}$, $t \in \mathcal{N}$.

Network Planning Constraints: We define the following Boolean variables. The BS deployment indicator $\mathsf{b}_x = 1$ if a BS is installed on site $x \in \mathcal{N}$, and $\mathsf{b}_x = 0$ otherwise. The TP assignment indicator $\mathsf{p}_{m,n} = 1$ if TP $m \in \mathcal{M}$ is served by BS $n \in \mathcal{N}$, and $\mathsf{p}_{m,n} = 0$ otherwise. The inter-RES power line connection indicator for each BS $\mathsf{c}_{t,n} = 1$ if BS $t \in \mathcal{N}$, $n \in \mathcal{N}$ are connected by a power line, and $\mathsf{c}_{t,n} = 0$ otherwise. We then have

$$\mathsf{p}_{m,n} \leq \mathsf{b}_n, \mathsf{c}_{t,n} \leq \mathsf{b}_n, \mathsf{c}_{t,n} \leq \mathsf{b}_t. \tag{1}$$

We further assume the following constraints. Each TP has to be connected to exactly one BS, i.e.,

$$\sum_{n \in \mathcal{N}} \mathsf{p}_{m,n} = 1, \forall m \in \mathcal{M}. \tag{2}$$

The number of TPs served by each BS is upper bounded, such that

$$\sum_{m \in \mathcal{M}} \mathsf{p}_{m,n} \leq B\mathsf{b}_n, \forall n \in \mathcal{N}, \tag{3}$$

where B is, without a loss of generality, the maximum number of TPs served by each BS, i.e. total radio resources available to each BS. Each BS is assumed to occupy the entire spectrum, i.e., factor-1 reuse strategy is adopted.

Propagation Environment: We use $\mathbf{H} \triangleq [h_{m,n}]_{M \times N}$ to denote the channel-dependent propagation gain matrix where $h_{m,n}$ is the long-term propagation gain of the link between TP m (averaged over all users in TP m) and BS n [3, Sec. III-A]. Denoting δ_m as the thermal noise power at TP m and P_n as the total transmission power of BS n for each associated TP, we define SINR between TP m and BS n as $\mathsf{SINR}_{m,n} = P_n h_{m,n} \left(\sum_{t \neq n} \rho_t P_t h_{m,t} + \delta_m \right)^{-1}$, $\forall m \in \mathcal{M}$, $n \in \mathcal{N}$, where $\rho_t = \sum_{j \in \mathcal{M}} \mathsf{p}_{j,t}/B$ denotes the ratio of occupied resources to all available resources at BS t [6, Eq. (10)]. In addition, TP m has a minimum QoS requirement defined in SINR terms, γ_m, such that $\mathsf{SINR}_{m,n} \geq \mathsf{p}_{m,n}\gamma_m$, $\forall m \in \mathcal{M}, n \in \mathcal{N}$. For the ease of subsequent discussion we transform the non-linear QoS constraint into an equivalent linear formulation through [7, Sec. IV-C] as

$$\mathsf{SINR}_{m,n} \geq \mathsf{p}_{m,n}\gamma_m \Leftrightarrow$$

$$M_{m,n}(1 - \mathsf{p}_{m,n}) + P_n h_{m,n} \mathsf{p}_{m,n} \geq$$

$$\gamma_m \left(B^{-1} \sum_{t \neq n} \sum_{j \in \mathcal{M}} \mathsf{p}_{j,t} P_t h_{m,t} + \delta_m \right), \tag{4}$$

where $M_{m,n} = \gamma_m \left(\sum_{t \neq n} P_t h_{m,t} + \delta_m \right)$ is a sufficiently large constant such that (4) holds for any $\mathsf{p}_{m,n} \in \{0,1\}, \forall m \in \mathcal{M}, \ n \in \mathcal{N}$.

Power Outage Constraints: The energy consumption of each BS is limited by the sum of its all energy sources. Thus, an energy outage happens at BS n when its energy supply is insufficient for the energy demand to serve its users. Setting a very small upper bound of the energy outage probability for each BS n, φ_n, (to limit energy supply loss due to, e.g., blackout) yields the following constraint

$$\mathsf{b}_n \left(\sum_{m \in \mathcal{M}} \mathsf{p}_{m,n} P_n + P_n^{(o)} - P_n^{(g)} + \sum_{t \neq n} P_{n,t} \mathsf{c}_{n,t} - \right.$$
$$\left. \sum_{t \neq n} (1 - \varepsilon_{t,n}) P_{t,n} \mathsf{c}_{t,n} - I_n^{(r)}(\varphi_n) \right) \leq 0, \forall n \in \mathcal{N}, \tag{5}$$

where $\varepsilon_{t,n} \in [0,1]$ is the energy loss factor on the power line between RES t and n^2, $P_n^{(o)}$ is the required static power for operating BS, e.g., cooling, baseband processing [8], and $I_n^{(r)}(\cdot)$ is the inverse of $F_n^{(r)}(z_n) = \int_0^{z_n} f_n^{(r)}(\xi) d\xi$.

III. PROBLEM FORMULATION VIA OPTIMIZATION

The objective is to select a subset of candidate BSs within $\mathcal{N}$ and to assign TPs within $\mathcal{M}$ to an available BSs taking into account the QoS requirement, BSs installation, inter-RES connection cost, and the electric grid consumption. Combining the constraints from Section II we obtain the following optimization problem

$$\min_{\{\mathsf{p}_{m,n}, \mathsf{c}_{t,n}, \mathsf{b}_n, P_n^{(g)} \geq 0, P_{t,n} \geq 0\}} \underbrace{\sum_{n \in \mathcal{N}} c_n \mathsf{b}_n}_{(i)} + \underbrace{\sum_{t,n \in \mathcal{N}} c_{t,n} \mathsf{c}_{t,n}}_{(ii)} +$$
$$\underbrace{\lambda T \left(\sum_{n \in \mathcal{N}} P_n^{(g)} \mathsf{b}_n + \sum_{t,n \in \mathcal{N}} \varepsilon_{t,n} P_{t,n} \mathsf{c}_{t,n} \right)}_{(iii)} \tag{6a}$$

subject to (1), (2), (3), (4), (5). \hfill (6b)

The terms (i) and (ii) correspond to the total installation and the connection cost, respectively. The term (iii) characterizes the cost of consumed power from the electric grid, where λ is the energy price expressed in cost unit/kWh, and T is the specified life cycle of the deployed cellular network. Sum of

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^{2}With $\varepsilon_{t,n}$ we guarantee that we do not deploy inter-RES links to transfer negligible amounts of energy between RESs.

(i)–(iii) terms in (6a) denotes CAPEX and OPEX. Note that consideration of the random energy arrivals to the harvesters in our planning framework are considered in (6b) through (5).

Proposition 1: Problem (6) is NP-hard.

Proof: (Sketch) Following [3], the problem of (6) can be reduced to an uncapacitated facility location problem which is NP-hard [3, Eq. (3)–(6) and Sec. IV] and implies NP-hardness of (6). $\square$

IV. PROBLEM SOLUTION VIA HEURISTIC

To solve (6), we propose a heuristic that decomposes (6) into two decoupled subproblems. The first subproblem is the QoS-aware BS deployment (that deploys BSs and connect TPs to BSs according to the energy distribution of BSs, assuming all candidate BSs are disconnected). The second subproblem is the energy balancing (that further reduces the total cost of network operators by balancing the benefits given through energy sharing among deployed BSs and their RESs and the incurred cost on BSs connection).

A. QoS-Aware BS Deployment

First, we assume that no inter-RES connections are possible, i.e., $c_{t,n} = P_{t,n} = 0$, $\forall n, t \in \mathcal{N}$. Defining $\mathbb{C}_1(\mathbf{v}, \mathbf{w}) = \sum_{n \in \mathcal{N}} c_n v_n + \lambda T \sum_{n \in \mathcal{N}} w_n v_n$, where $\mathbf{v} = [v_n]_{N \times 1}$, $\mathbf{w} = [w_n]_{N \times 1}$, (6) reduces to

$$\min_{\{p_{m,n}, b_n, P_n^{(g)} \geq 0\}} \mathbb{C}_1(\mathbf{b}, \mathbf{P}) \tag{7a}$$

$$\text{subject to (1), (2), (3), (4),} \tag{7b}$$

$$b_n \left(\sum_{m \in \mathcal{M}} p_{m,n} P_n + P_n^{(o)} - P_n^{(g)} - I_n^{(r)}(\varphi_n) \right) \leq 0, \tag{7c}$$

where $\mathbf{b} \triangleq [b_n]_{N \times 1}$, $\mathbf{P} \triangleq [P_n^{(g)}]_{N \times 1}$.

Proposition 2: Suppose an optimal solution to (7) exists, denoted as a 3-tuple $\{\mathbf{b}^*, \mathbf{p}^*, \mathbf{P}^*\}$, where $\mathbf{p} \triangleq [p_{m,n}]_{M \times N}$ and $*$ symbol denotes optimality. Defining $\Delta_n(\mathbf{u}) \triangleq -\sum_{m \in \mathcal{M}} u_{m,n} P_n - P_n^{(o)} + I_n^{(r)}(\varphi_n)$, where $\mathbf{u} = [u_{m,n}]_{M \times N}$, then

$$P_n^{(g)*} b_n^* = \max \{-\Delta_n(\mathbf{p}^*) b_n^*, 0\}, \tag{8}$$

where $\Delta_n(\mathbf{p}^*)$ is the remaining energy from RES applied to transmission and operation of BS.

Proof: For $b_n^* = 1$, (7c) reduces to $P_n^{(g)} \geq -\Delta_n(\mathbf{p})$, which together with $P_n^{(g)} \geq 0$ implies that

$$P_n^{(g)} \geq \max \{-\Delta_n(\mathbf{p}), 0\}, \quad \forall n \in \mathcal{N}. \tag{9}$$

As the objective function of (7) is strictly increasing in $P_n^{(g)}$, $\forall n \in \mathcal{N}$, when $b_n^* = 1$, we conclude that (9) will be always tight in the optimal condition, i.e., $P_n^{(g)*} = \max\{-\Delta_n(\mathbf{p}^*), 0\}$, $\forall n \in \mathcal{N}$. On the other hand, (8) holds when $b_n^* = 0$. $\qquad\square$

Applying (8) to (7) yields

$$\min_{\{b_n, p_{m,n}\}} \lambda T \sum_{n \in \mathcal{N}} \max\left\{\frac{c_n}{\lambda T} - \Delta_n(\mathbf{p}), \frac{c_n}{\lambda T}\right\} b_n \tag{10a}$$

$$\text{subject to (7b).} \tag{10b}$$

Notice that solution to (10) is equal to the solution to the original problem (7). From (10) follows that it is beneficial to deploy BSs at sites with positive $\Delta_n(\mathbf{p})$, and to connect TPs to the deployed BSs with surplus renewable energy. We devise a heuristic to solve (10) (i.e. an algorithm that reaches as close as possible to a final solution) which is presented in Algorithm 1. Therein, (for ease of exposition) the total radio resources are assumed sufficient for network planning, i.e. $BN \geq M$. Note that Algorithm 1 might not output the assignment for all existing TPs when, e.g., QoS requirements are too strict. In this case, e.g., new positions (or the number) of BS must be considered and Algorithm 1 must run again. The convergence for Algorithm 1 can be achieved in at most N outer loops, where the worst case represents reaching $\mathcal{N} = \varnothing$.

B. Energy Balancing Inter-RES Connection

Let $\tilde{\mathcal{N}}$ denote the set of deployed BSs based on $\tilde{\mathbf{b}}, \tilde{\mathbf{p}}, \tilde{\mathbf{P}}$ (i.e. the output of Algorithm 1). Defining $\mathbb{C}_2(\mathbf{x}, \mathbf{y}, \mathbf{z}) \triangleq \lambda T \left\{\sum_{t,n \in \tilde{\mathcal{N}}} \left(\varepsilon_{t,n} z_{t,n} c_{t,n} + \frac{x_{t,n}}{\lambda T} c_{t,n}\right) + \sum_{n \in \tilde{\mathcal{N}}} \left(y_n + \frac{c_n}{\lambda T}\right)\right\}$, where $\mathbf{x} = [x_{t,n}]_{N \times N}$, $\mathbf{y} = [y_n]_{N \times 1}$, and $\mathbf{z} = [z_{t,n}]_{N \times N}$. After the QoS-aware BS deployment shown in Section IV-A, (6) further reduces to

$$\min_{\{c_{t,n}, P_n^{(g)} \geq 0, P_{t,n} \geq 0\}} \mathbb{C}_2(\mathbf{C}, \mathbf{P}, \mathbf{R}) \tag{11a}$$

$$\text{subject to (5) with } p_{m,n} \text{ from } \tilde{p}, \text{ replacing } \mathcal{N} \text{ by } \tilde{\mathcal{N}}, \tag{11b}$$

where $\mathbf{C} \triangleq [c_{t,n}]_{N \times N}$ and $\mathbf{R} \triangleq [P_{t,n}]_{N \times N}$.

We propose a second heuristic (algorithmic solution) given in Algorithm 2 to reach as close as possible to a solution of (11). The heuristic starts with a fully connected RESs topology, with a set of inter-RES connections denoted as $\mathcal{E} \triangleq \{e_{t,n}\}_{t,n \in \tilde{\mathcal{N}}}$. Within each iteration of the heuristic, the inter-RES power lines transferring the least amount of energy are removed from $\mathcal{E}$ until no cost saving can be achieved. Notice that $\{\tilde{\mathbf{C}} = [1]_{\forall t,n}; \tilde{\mathbf{P}}; \tilde{\mathbf{R}} = [0]_{\forall t,n}\}$ is a feasible solution to (11), thus the feasibility of Step 2 in

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Algorithm 1: QoS-aware BS deployment

Input: $\forall m, n, t$: $\mathcal{N}$; $\mathcal{M}$; $c_{t,n}$, P_n, δ_m, φ_n, c_n, $P_n^{(o)}$, B (s.t. $BN \geq M$), $\varepsilon_{t,n}$, γ_m; $f_n^{(r)}(z_n)$; $\mathbf{H}$

1: connect all TPs to closest BSs with free (unassigned) radio resources

2: $\Omega := \{m | \sum_{n \in \mathcal{N}} \mathsf{SINR}_{m,n} \mathsf{p}_{m,n} < \gamma_m, m \in \mathcal{M}\}$, i.e. infeasible TPs

3: **if** $\Omega = \varnothing$ **then**

4:     $F := 1$; $\hat{\mathbf{p}} := \mathbf{p}$; $\hat{\mathbf{b}} := \mathbf{b}$; $\hat{\mathbf{P}} := \mathbf{P}$

5:     **repeat**

6:         from BS set with least number of TPs, i.e., $n_\diamond \in \arg\min_{n \in \mathcal{N}} \sum_{m \in \mathcal{M}} p_{m,n}$, randomly select one and disconnect its associated TPs, i.e., $\mathcal{M}_\diamond$

7:         **for all** TP $m \in \mathcal{M}_\diamond$ **do**

8:             find b_n by assigning TP m to the closest BS n (except $n_\diamond$) with positive $\Delta_n(\mathbf{p})$ without violating (3)

9:             **if** such b_n exists **then**

10:                 $\mathsf{p}_{m,n} = 1$, $n \in \mathcal{N}$; $\mathcal{M}_\diamond := \mathcal{M}_\diamond \backslash \{$TP $m\}$

11:             **else**

12:                 $\mathsf{p}_{m,n} = 0$, $n \in \mathcal{N}$

13:             **end if**

14:         **end for**

15:         $\Omega := \{m | \sum_{n \in \mathcal{N}} \mathsf{SINR}_{m,n} \mathsf{p}_{m,n} < \gamma_m, m \in \mathcal{M}\}$

16:         **if** $\Omega = \varnothing$ and $\mathcal{M}_\diamond = \varnothing$ **then**

17:             $\mathcal{N} := \mathcal{N} \backslash \{n_\diamond\}$; $\hat{\mathbf{p}} := \mathbf{p}$; $\hat{\mathbf{b}} := \mathbf{b}$; $\hat{\mathbf{P}} := \mathbf{P}$

18:         **end if**

19:     **until** $\Omega \neq \varnothing$ or $\mathcal{N} = \varnothing$

20: **else**

21:     $F := 0$

22: **end if**

Output: $F := 0$: no solution found; $F := 1$: $\tilde{\mathbf{p}} := \hat{\mathbf{p}}, \tilde{\mathbf{b}} := \hat{\mathbf{b}}, \tilde{\mathbf{P}} := \hat{\mathbf{P}}$, i.e. optimized BS configuration

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Algorithm 2 always holds. In addition, termination criteria for the loop (Step 1–5) in Algorithm 2 are achievable within $|\mathcal{E}|$ loops.

C. Heuristics Complexity Analysis

The complexity of Algorithm 1 is determined by the double-nested loop (Step 5–19) whose complexity is $O(MN^2) = O(N^3)$ since $M = O(N)$, i.e., the number of TPs is limited by $M \leq BN$. The complexity of Algorithm 2 is governed by the time needed to solve a Linear Program (LP) (Step 2). As each LP can be solved in polynomial time [9, Theorem 8.5] its complexity is $O(X^t)$, where X is the number of LP variables and t characterizes the running time of the LP solver. Thus the complexity of Algorithm 2 is $O(X)O(X^t)$ for $X = N^2$. In turn, the complexity of the complete heuristic (Algorithm 1 and Algorithm 2) is $O(N^{2t+2})$.

Algorithm 2: Energy Balancing inter-RES Connection Deployment

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Input: complete set of inter-RES connections $\mathcal{E}$; $\forall t, n$: $\varepsilon_{t,n}$, c_n; $\tilde{\mathbf{p}}, \tilde{\mathbf{b}}, \tilde{\mathbf{P}}$ from Algorithm 1; $\mathbb{S} \triangleq \infty$

1: **repeat**
2:    find $\tilde{\mathbf{C}}, \tilde{\mathbf{P}}, \tilde{\mathbf{R}}$, i.e. the solution of (11), with $\tilde{\mathbf{p}}, \tilde{\mathbf{b}}$, $\mathsf{c}_{t,n} = 1$ $\forall e_{t,n} \in \mathcal{E}$
3:    target zero and the smallest positive $P_{t,n}$ in $\tilde{\mathbf{R}}$, then remove corresponding connections from $\mathcal{E}$, i.e., $\mathcal{E} := \mathcal{E} \backslash \{e_{t,n}\}$
4:    $\mathbb{S} := \min\left\{\mathbb{S}, \mathbb{C}_2(\tilde{\mathbf{C}}, \tilde{\mathbf{P}}, \tilde{\mathbf{R}})\right\}$
5: **until** $\mathbb{C}_2(\tilde{\mathbf{C}}, \tilde{\mathbf{P}}, \tilde{\mathbf{R}}) > \mathbb{S}$ or $\mathcal{E} = \varnothing$
6: **if** $\mathbb{C}_1(\tilde{\mathbf{b}}, \tilde{\mathbf{P}}) < \mathbb{S}$ **then**
7:    $\mathcal{E} := \varnothing$
8: **end if**

Output: optimized inter-RES connections according to $\mathcal{E}$

V. NUMERICAL RESULTS

As an illustrative simple example we consider a $3\,\text{km} \times 3\,\text{km}$ area where m TPs are arbitrarily located and n BS candidate sites (forming a grid) are identified to provide services for TPs. For a cost unit of $€$ we assume all RES-enabled BSs have fixed and equal installation cost, c_n [10, Sec. II-B] and fixed transmission power [7, Sec. II-C]. Furthermore, for a fair comparison we assume that all traditional (no-RES enabled) BSs have an installation cost of $\bar{c}_n$ and find optimal cellular network structure using Algorithm 1 considering no RES and no inter-RES connections. Assuming distance-dependent pathloss-only scenario, the elements of $\mathbf{H}$ are given as $h_{m,n} = 10^{\frac{-\{L_A + L_B \log_{10}(d_{m,n}/\text{km})\}}{10}}$ [6, Eqs. (1), (7)], where $d_{m,n}$ denotes the distance between TP m and BS n and L_A and L_B are the empirical constants provided by [11].

As the distribution of harvested power at location n is scenario-dependent, for simplicity we assume it being uniformly distributed, i.e., $f_r^{(n)}(z_n) = \frac{1}{b_n - a_n}$, $\forall z_n \in [a_n, b_n]$, $n \in \mathcal{N}$, with a_n and b_n being the minimum and maximum harvested power at location n, respectively (note that we can use any continuous energy distribution in our model). All deployment parameters are summarized in Table I, representing values describing typical network scenario, following, e.g. [3], [4], [11]. Numerical results are generated based on the method of batch means with 100 simulation runs for the confidence level of 95%. Due to space constraints we focus on two most representative cases.

A. CAPEX and OPEX versus Network Life Cycle

The result is presented in Fig. 1(a). For each simulation run new location points for BS and TPs (with the respective $\mathbf{H}$) have been randomly generated. We immediately observe that the introduction of RESs into network planning brings cost saving to the operator, compared to the traditional deployment structure. This benefit is slightly boosted by the energy balancing among RESs, as for the considered network

TABLE I

PARAMETER VALUES USED IN THE NUMERICAL EVALUATION

No. candidate sites	$N = 9$	Network life cycle	$T = [6, 20]$ years
No. TPs	$M = 20$	Electricity price	$\lambda = 0.3\,€/\text{kWh}$
No RES-based BS depl.	$\bar{c}_n = 55\,\text{k}€$	RES-based BS depl.	$c_n = 60\,\text{k}€$
Inter-RES conns. cost	$c_{t,n} = 10\,€/\text{m}$	BSs oper. power	$P_n^{(o)} = 19\,\text{W}$
Transmission power	$P_n = 20\,\text{W}$	No. res. blocks	$B = \{6, 12\}$
Thermal noise power	$\delta_m = -114\,\text{dBm}$	SINR requirement	$\gamma_m = 0\,\text{dB}$
Propagation coeff. A	$L_A = 148.1\,\text{dB}$	Min harv. power	$a_n = [0, 100]\,\text{W}$
Propagation coeff. B	$L_B = 37.6\,\text{dB}$	Max harv. power	$b_n = [100, 200]\,\text{W}$
Power outage prob.	$\varphi_n = 5\%$	Energy loss	$\varepsilon_{t,n} = 1\%$

coeff.–coefficient; conns.–connections; depl.–deployment; harv.–harvested; no.–number; oper.–operational; prob.–probability; res.–resource; reported values are equal $\forall m, n, t$
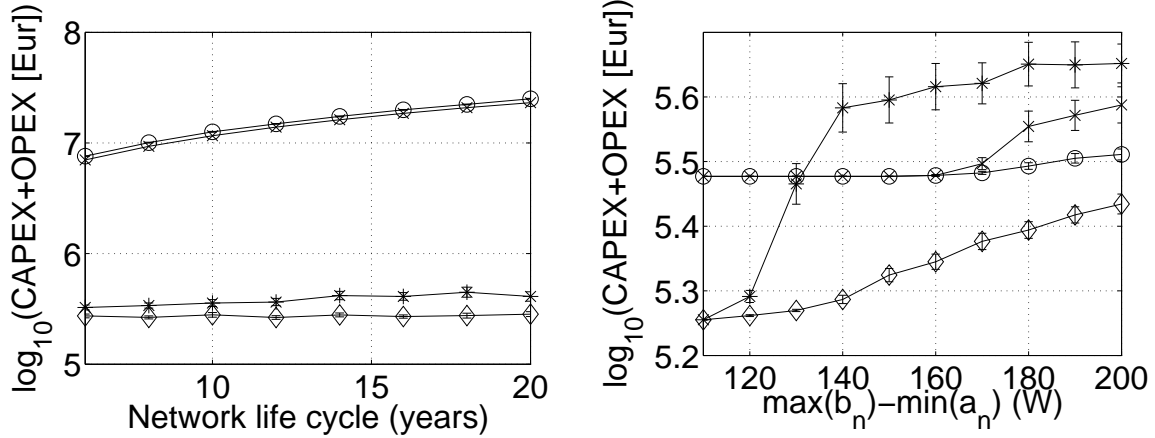
(a) $\times$: No REs (optimal depl. via FICO®Xpress); $\circ$: No inter-RES conns. (Alg. 1); $*$: No RES (Alg. 1); $\diamond$: Inter-RES conns.

(b) $\times$: No inter-RES conns. ($B = 6$); $\circ$: Inter-RES conns ($B = 6$); $*$: No inter-RES conns. ($B = 12$); $\diamond$: Inter-RES conns. ($B = 12$) (Alg 1.+Alg. 2)

Fig. 1. CAPEX and OPEX as a function of: (a) network life cycle T, for randomly chosen a_n, b_n from Table I for each location n and $B = 12$; (b) harvested energy spread $\max b_n - \min a_n$ for $T = 10$ years, where for each simulation point (from left to right) $k = 0, \ldots, 9 : E[z_n] = 145 - 5k$ (W); whiskers denote 95% confidence interval; alg.–algorithm; depl.–deployment; conns.–connections.

configuration, per BS, most of the energy is provided by the RES alone. Notice that CAPEX and OPEX with inter-RESs connections does not vary with the network life cycle, as the whole network is basically self-powered (without grid power). Comparing the effectiveness of the developed algorithmic solution (considering the lack of RESs) with the solution to (6), computed using FICO® Xpress Optimization Suite version 1.23.00, for 10 independent realizations of **H**, we conclude that our heuristic is close to the optimal deployment.

B. CAPEX and OPEX versus Harvested Energy Spread

The result is given in Fig. 1(b) for one randomly generated set of TP locations, with the respectively generated $\mathbf{H}$ (one time only). CAPEX and OPEX roughly increases as the difference between $\min a_n$ and $\max b_n$ becomes larger, irrespective of B. This is because of strong randomness in available energy, which in turn incurs extra cost on electricity supply (no inter-RES connections) or power lines (inter-RES connections). In addition, we also observe that deploying inter-RES connections with large B is the most cost-effective option for network operators. This is because BSs with large B normally allow the small number of deployed BSs thus saving the deployment cost, while also lead to large energy deficiency at some 'crowed' BSs. This is especially visible with high variance of harvested power, which increases a benefit of RES use by deploying inter-RES connections.

VI. CONCLUSIONS

In this letter we have developed a novel cellular network planning framework considering the use of renewable energy sources and energy balancing. For the posed problem we have developed a novel heuristic. Our numerical results demonstrate CAPEX and OPEX savings in comparison to traditional deployment strategies.

REFERENCES

[1] P. Pawełczak, M. Zheng, S. Stańczak, and H. Yu, "Enriching cellular networks with dynamic spectrum access and energy harvesting: a network planning case," in *Proc. IEEE DySPAN*, Bellevue, WA, USA, Oct. 16–19, 2012.

[2] D. W. K. Ng, E. S. Lo, and R. Schober. Energy-efficient resource allocation in OFDMA systems with hybrid energy harvesting base station. [Online]. Available: http://arxiv.org/abs/1302.4721

[3] E. Amaldi, A. Capone, and F. Malucelli, "Planning UMTS base station location: Optimization models with power control and algorithms," *IEEE Trans. Wireless Commun.*, vol. 2, no. 5, pp. 939–952, Sept. 2003.

[4] K. Johansson, "Cost effective deployment strategies for heterogeneous wireless networks," Ph.D. dissertation, KTH, Stockholm, Sweden, Nov. 2007.

[5] Y.-K. Chia, S. Sun, and R. Zhang, "Energy cooperation in cellular networks with renewable powered base stations," in *Proc. IEEE WCNC*, Shanghai, China, Apr. 7–10, 2013. [Online]. Available: http://arxiv.org/abs/1301.4786

[6] I. Viering, M. Döttling, and A. Lobinger, "A mathematical perspective of self-optimizing wireless networks," in *Proc. IEEE ICC*, Dresden, Germany, June 14–18, 2009.

[7] M. Johansson and L. Xiao, "Cross-layer optimization of wireless networks using nonlinear column generation," *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp. 435–445, Feb. 2006.

[8] G. Auer, V. Giannini, C. Desset, I. Gódor, P. Skillermark, M. Olsson, M. A. Imran, D. Sabella, M. J. Gonzalez, O. Blume, and A. Fehske, "How much energy is needed to run a wireless network?" *IEEE Wireless Commun. Mag.*, vol. 18, no. 5, pp. 40–49, Oct. 2011.

[9] C. H. Papadimitriou and K. Steiglitz, *Combinatorial Optimization: Algorithms and Complexity*. Prentice-Hall, 1982.

[10] P. González-Brevis, J. Gondzio, Y. Fan, H. V. Poor, J. Thompson, and I. Krikidis, "Base station location optimization for minimal energy consumption in wireless networks," in *Proc. IEEE VTC-Spring*, Budapest, Hungary, May 15–18, 2011.

[11] *Further advancements for EUTRA: Physical layer aspects (release 9)*, 3GPP TR 36.814 v2.0.1, Mar. 2010.